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Dickie, R., Cahill, R., Fusco, V. F., & Kangas, V. (2016). 229 GHz FSS for the MetOp Second Generation Microwave Sounder Instrument. In 2016 10th European Conference on Antennas and Propagation (EuCAP). (pp. 1-4). Institute of Electrical and Electronics Engineers Inc.. DOI: 10.1109/EuCAP.2016.7481779

Published in:
2016 10th European Conference on Antennas and Propagation (EuCAP)

Document Version:
Peer reviewed version

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R. Dickie[1], R.Cahill[1], V.F. Fusco[1], V. Kangas[2]

[1] The Institute of Electronics, Communications and Information Technology (ECIT), Queen's University Belfast, Northern Ireland Science Park, Queen's Road, Queen's Island, Belfast BT3 9DT, Northern Ireland, UK, r.dickie@qub.ac.uk

[2] The European Space Agency (ESA), Keplerlaan 1, PO Box 299, NL 2200 AG Noordwijk, The Netherlands

***Abstract*—This paper describes the design of a frequency selective surface (FSS) which provides transmission of 228 - 230 GHz radiation and rejection from 164 – 191.3 GHz with insertion losses under 0.25 dB for TE wave polarization at 45° incidence. This state-of-the art filter consists of two air spaced freestanding perforated screens, comprising unit cell elements of resonant slots folded for the purpose of miniaturisation to enhance angular stability. The reported geometry enhances the angular stability (45° ± 10°) of the FSS beyond what is possible with canonical linear slots and satisfies the stringent electromagnetic performance requirements for signal demultiplexing in the quasi-optical feed train of the Microwave Sounder (MWS) instrument.**

***Index Terms*— atmospheric science instrumentation, frequency selective surface, FSS, microwave**

I. INTRODUCTION

FSS are key components in the quasi-optic network (QON) of the MWS [1, 2] cross-track scanner radiometer where they spatially direct the incoming radiation from the Earth's atmosphere, according to frequency, to the corresponding instrument receivers. At microwave frequencies clouds are largely transparent, and the sounder can probe inside and below clouds. The MWS provides measurements of temperature, water vapour profiles and information on cloud liquid water. The satellite data is operationally used in numerical weather predictions and has a significant impact on forecast accuracy [3]. The accuracy of NWP systems in temperature and humidity fields drives stringent performance specifications for MWS, especially in terms of stability and noise performance In addition, in order to satisfy satellite payload constraints on cost, mass and energy consumption, the MWS is a single unit instrument with a mechanically scanning reflector antenna to collect radiation over a wide field of view. It simultaneously receives signals in 24 channels with centre frequencies at 23.8, 31.4, 54, 89 165.5, 183 and 230 GHz. This large operating frequency range combined with low loss imposes stringent requirements on the FSS that are deployed in the QON after the antenna. Four FSS are required and are orientated at 45° incidence in either TE or TM polarization, to provide a compact instrument design: Fig. 1. The first and second dichroic elements in the network, labeled FSS 1 and FSS 2, have been described previously [4, 5]. The fourth FSS, labeled FSS 4, is the topic of this paper. The structure has a scientific requirement to operate as a high pass filter for TE polarised signals and meet the performance specification given in Table 1. This research exploits computational electromagnetic modelling and previously developed advanced micromachining processes [6-9], to create ultra-low loss high angular stability FSS. The study will establish the feasibility of the design which can be deployed in the QO receiver of the instrument in order to separate the signals in the 229 GHz band (0.9% bandwidth) from those that are received in the 165.5 (1.8%) and 183 GHz (8.7%) channels. In order to achieve high receiver sensitivity, the maximum specified loss in all three bands is 0.25 dB for a 45° ± 10° incident beam.

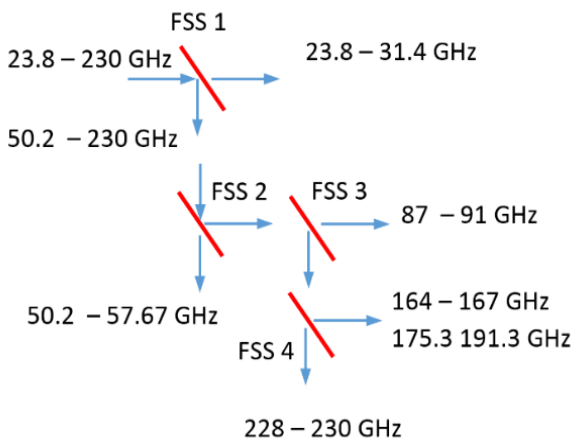

Fig. 1. MWS breadboard frequency demultiplexing scheme

TABLE I. FSS 4 SPECIFICATION REQUIREMENTS

Parameter	Requirement
Transmission Band Loss Target	228 - 230 GHz < 0.25 dB
Reflection Band (1) Loss Target	175.3 – 191.3 GHz < 0.25 dB
Reflection Band (2) Loss Target	164 - 167 GHz < 0.25 dB
Incident Angle (theta) Polarization	45° ± 10 ° TE
Physical Diameter Optical Diameter	100 mm 80 mm

II. DESIGN

The FSS is designed to meet the performance specifications that are listed in Table 1. This requires separation of TE polarized waves incident on the FSS at 45° to the direction of propagation with an insertion loss <0.25 dB in two reflection bands spanning 164 – 167 GHz and 175.3 – 191.3 GHz, and one transmission band which covers the range 228 – 230 GHz. To meet the low insertion loss requirements, freestanding FSS topology [7] has been employed. The design was developed in CST Microwave Studios frequency domain solver [10], which exhibits high accuracy in predicting the spectral performance of freestanding FSS operating in the mm wave band [9]. The structure is composed of two closely spaced metal arrays perforated with linear aperture elements. A schematic and the dimensions of a single unit cell of the preliminary FSS design are depicted in Fig. 2 in addition to the direction of propagation and polarisation of the incident waves. Due to the fact that the active region of each screen is 100 µm thick, this structure is mechanically more robust than previously developed freestanding FSS [8], whose thickness were typically 10 µm. The linear slots are 646 µm long by 140 µm wide, and the modelled copper surface conductivity is 5.8×10^7 S/m. The periodic arrays are identically laid out with their slot apertures aligned in the z-axis. Each screen is separated by a 331 µm air gap which provides an impedance match close to the pass band frequency (~ 232 GHz) of the individual slots excited in the $\lambda/2$ mode. The combination of resonance slots and cascaded matched screens provides a dual mechanism to tailor the performance in the reflection and transmission bands. The computed s-parameters, transmission and reflection coefficients of the baseline design is shown over the range 150 - 250 GHz at 45° incidence in Fig. 3. The maximum passband insertion loss is 0.21 dB, with reflection losses of 0.08 dB (183 GHz), and 0.02 dB (165 GHz). However although the FSS meets the target maximum loss requirement (0.25 dB) at nominal incidence, this is not the case at 35° and 55° where the maximum computed loss increases to 2.43 dB (not plotted for brevity).

This work was carried out under ESTEC Contract No. 4000107540/13/NL/BJ

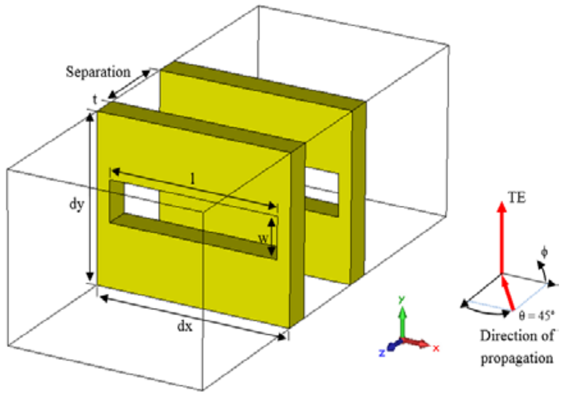

Fig. 2. Unit cell of the linear slot FSS (yellow shows metal), polarisation and direction of proagation also identified. Dimensions (µm) dx = 745, dy = 564, t = 100, S = 331, l = 646, w = 140

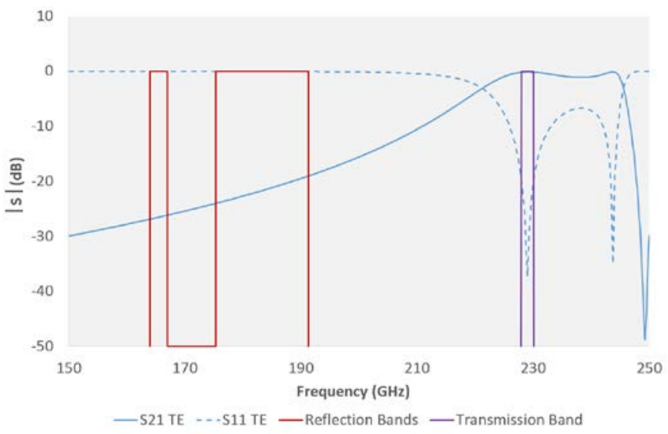

Fig. 3. Modelled s-parameter electromagnetic performance of the linear slot FSS TE polarised design, covering the range 150 – 250 GHz.

To enhance the angular stability of the FSS, a design modification was carried out, to miniaturise the physical dimensions of the slot element, and hence reduce the size of the unit cell. The modified geomtery is depicted in Fig. 4, and is an 'I' shaped slot which has a significantly more compact unit cell arrangment than was employed in the preliminary design. The unit cell periodicities dx and dy are now reduced to 500 µm and 356 µm respectively. This provides over a 30% reduction in periodicity compared to the modelled linear slot values. The s-parameter electromagnetic performance of the miniaturised FSS design is shown in Fig. 5, now transmission losses are reduced by 0.04 dB because of the flatter passband response, and by carefully positioning the 228 - 230 GHz band close to the center of this region, losses observed for angular variations about 45° incidence are also reduced. The maximum losses in each reflection band remain constant at 0.08 dB (183 GHz), and 0.02 dB (165 GHz). Importantly, the design exhibits a significant improvement in angular stability, with maximum losses reduced from 2.43 dB to 0.26 dB for theta ± 10°. S-parameter measured results for the design are presented in Figures 6 – 7 for the transmission and reflection bands respectively. Both show good agreement, with measured insertion losses slightly lower than predictions.

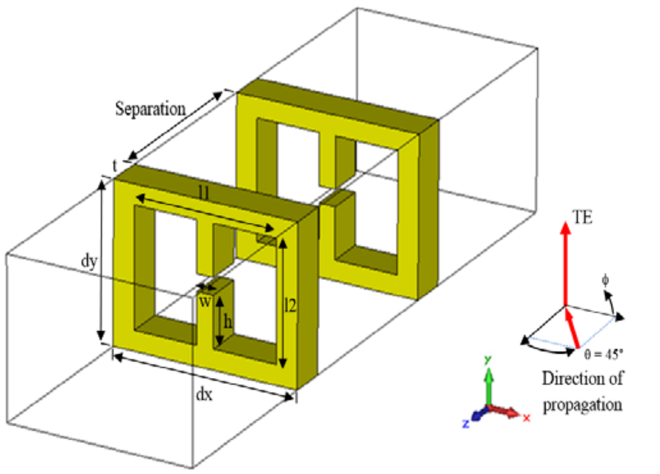

Fig. 4. Unit cell of the miniaturised I-slot design. Dimensions (μm) dx = 500, dy = 356

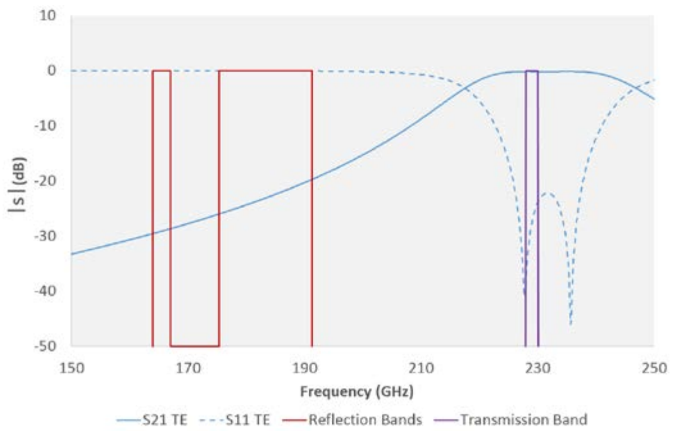

Fig. 5. Modelled s-parameter electromagnetic performance of the I-slot FSS TE polarised design, covering 150 – 250 GHz

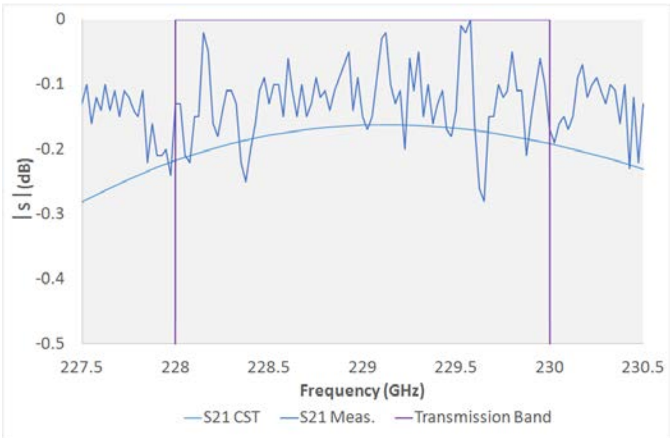

Fig. 6. Measured transmission band, and CST predictions, covering 228 – 230 GHz

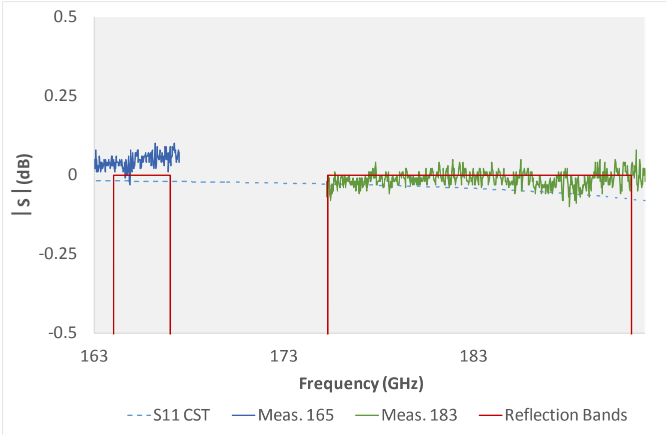

Fig. 7. Measured 164-167 GHz and 175.3 – 191.3 GHz reflection bands compared to the CST predictions

III. CONCLUSIONS

We have developed an ultra-low insertion loss high-pass FSS using freestanding technology. The FSS operates at high 45˚ incidence, providing for a compact radiometer layout. Transmission at 228 – 230 GHz shows measured losses under 0.2 dB and the two reflection bands centered at 165 and 183.3 GHz both display measured losses under the maximum of 0.05 dB obtained from computer predictions. This FSS design therefore meets the performance requirements specified for the QO receiver of the MWS instrument.

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